

A STRINGY COMPOSITE GRAVITON AND THE COSMOLOGICAL CONSTANT PROBLEM

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ABSTRACT

A heuristic model of a composite graviton is presented motivated by open string field theory. The model simply assumes a composite closed string sector, world sheet conformal invariance and the observed open string states, i.e., standard model particles, as an input. A UV to IR map from the open string to the closed string sectors naturally emerges. The IR cutoff of the lightest observed fermion loops gets mapped to a UV cutoff for the scalar mode of the graviton/dilaton. This provides a UV cutoff for gravity via the dilaton coupling to G . Based on recent estimates of the lightest fermion (neutrino) mass this gives an energy cutoff for the graviton near the current estimates of the dark energy density of 10^{-3} eV.

1. INTRODUCTION

The cosmological constant problem is arguably the greatest problem currently facing string theory or any other approach to quantum gravity. [1] The reason this problem is so significant is that involves energy scales which are believed to be well understood by current theory. This has been driven home by the recent cosmological expansion data giving an effective cosmological constant or dark energy density of about 10^{-3} electron volts. The cosmological constant problem is therefore not a Planck energy scale problem but rather a problem involving energy scales on the order of 10^{-3} electron volts, an energy scale we thought we understood completely. On the other hand, if the cosmological constant problem truly is solved at the Planck energy scale then it becomes a fine tuning problem of unbelievable precision, i.e., a precision of 10^{-120} ! The current situation is so desperate that to many the anthropic principle seems to be the only way out. [2]

Perhaps as a result of this, the cosmological constant problem has recently been examined in a number of qualitative and/or phenomenological approaches to see if it is at least **possible** to address the problem outside of the anthropic principle. [3]¹ For example, it has recently been suggested by more than one author that the possible solution to the cosmological constant problem is in the nature of a composite graviton although the specific model for such a composite structure has generally not been discussed.² In unrelated work it has for some time been conjectured that a composite graviton could naturally arise in open string field theory. [4][6] Basically, the graviton propagator is derived from the open string loops. At present the technical details of such an approach are unresolved. Nonetheless, it seems quite possible that while this type of construction may be problematic for bosonic open string field theory such a construction could in principle be completed successfully in open superstring field theory. [5]

Another possible clue to the cosmological constant problem resides in the effective field theory view of gravity. Another way of looking at the cosmological constant problem is that our effective field theory low energy description of gravity at standard model energy scales must be missing something. If string theory is the correct description of nature this means some unexpected stringy effect must survive at energies far below the string scale, i.e., at a

¹The present paper is presented in this spirit as heuristic and admittedly speculative ideas previously limited to private communications are being vetted for a wider audience.

²E.g., see [3], A. Zee and R. Sundrum.

scale where general relativity is normally considered a completely accurate effective field theory. Therefore, the field theory limit of string theory may warrant closer inspection.

In this paper the above two considerations are combined to see if they can shed light on the cosmological constant problem. A completely heuristic approach is taken. It is simply assumed that a detailed construction of a composite graviton can eventually be done in the context of open superstring field theory, and the closed string sector arises from the open string loops. The approach is then backward in the sense that it starts from where we are (standard model energy scales), rather than starting from the string scale and working down as is normally done, but without adopting a field theory limit of the underlying string theory. The only other input is the open string spectrum we observe (i.e., the standard model particles). Although motivated by string field theory the stringy aspects incorporated are essentially conventional world sheet ideas. In particular the conformal invariance of the world sheet is employed to extract the graviton pole from the nonplanar equivalent of the open string loops along with a UV to IR map between the observed open string sector and a closed string composite sector/graviton sector. As a result of this map a composite graviton UV energy cutoff is related to the IR cutoff of the open sector vacuum loops. This IR cut off is the estimated Compton wavelength of the lightest standard model particle having the requisite loop structure, the neutrino. Reasonable estimates of the neutrino mass are in the order of 10^{-3} electron volts, providing a graviton UV cut off of the same order of magnitude as the estimated cosmological constant.³ A phenomenological modification to the graviton propagator is presented which incorporates this cut off.

Although this simple heuristic model does not solve the cosmological constant problem per se since it needs the neutrino mass as an input, it has some suggestive qualitative features which should survive in a more detailed string field theory construction. In particular, it suggests the cosmological constant problem may simply be another aspect of the hierarchy problem, or at least the aspect of the hierarchy problem related to the light fermion masses, which is hopefully more tractable. Other potentially attractive features of this model are also discussed.

³A connection between the neutrino mass and cosmological constant has also recently been proposed in a composite graviton model in [12], however, the specific model is quite different.

2. THE STRINGY COMPOSITE GRAVITON

As noted above a composite graviton constructed from the loops of an open string sector will simply be assumed.⁴ This is believed to be a not unreasonable assumption since the current status of open string field theory is suggestive that a complete construction of this type is possible. [5] There are other motivations as well and a general discussion of possible motivations for a composite closed string are found in [6]. [5] and [6] contain many additional references.

Ideally we would like to make detailed contact with the existing open string field theory models for further guidance. However, the current state of development is not really able to give much insight beyond suggesting a consistent open string theory with a composite closed sector is possible. In particular, superstring field theory does not yet exist in a form which can describe exactly how the closed string poles arise or what the relevant boundaries of moduli space are. Also, a composite closed sector may arise from another nonperturbative formulation of string theory, e.g., a matrix model, that will nonetheless presumably keep the key features of world sheet theory. Therefore, we instead fall back on world sheet ideas as a guide. Since we are only looking for a qualitative guide, it turns out that the only key stringy features we will need beyond assuming a composite model are world sheet conformal invariance and the world sheet modular parameter.⁵

We are assuming open sector loops in some sense define the closed sector. Our interest is thus in the (super)string annulus diagram describing open loop amplitudes and a nonplanar cylinder diagram for the closed sector.⁶ We will simply assume the amplitude structure is the same. The amplitude

⁴The term composite graviton is really a misnomer in this context and falsely suggests that the no go theorem of [13] should apply. However, the no go theorem of [13] assumes a completely consistent underlying field theory without a spin two state in which a spin two particle then emerges as a bound state. In contrast, open string theory without a closed sector is inconsistent and a “composite” closed sector is added at a fundamental level to make a consistent theory. The no go theorem is therefore not applicable. Since this is a purely stringy effect a “stringy composite graviton” as discussed here should be clearly distinguished from other “composite graviton” models which have appeared for many years.

⁵The basic world sheet ideas used are not new and essentially just follow the discussion in section 4 of [6].

⁶We know from standard arguments involving unitarity that some type of closed diagram with a pole structure is needed to make our open string theory consistent. See, e.g., section 3.1 of [7], vol. 1.

structure is determined by the integral over the world sheet modular parameter, which we will take as the cylinder modular parameter t , the ratio of cylinder circumference to length. The $t \rightarrow \infty$ limit is the IR part of the open sector annulus. This limit is not problematic, however, since such IR limits are well understood. At the other limit, $t \rightarrow 0$, the open string annulus amplitude blows up and is potentially dangerous. However, this limit is also conventionally interpreted as a soft IR limit, but of the closed strings, corresponding to arbitrarily long distance propagation of long skinny tubes. That is this edge of the world sheet integration has a singularity which can be represented (if we were to take a field theory limit) in the form of a field theory massless particle pole:

$$D(k) \sim 1/k^2$$

which allows the dangerous UV sector of the open loop to be reinterpreted as an infrared effect. Therefore, the short distance open string UV vacuum fluctuations naturally correspond to long distance propagation, the IR region of the closed string. The large open loops in turn correspond to short distance closed loop propagation, the UV region of the closed string. Therefore, we have the limits of the same amplitude structure mapped to two different regions of the open and closed sectors; the $t \rightarrow \infty$ limit corresponds to open sector IR, closed sector UV, and the, $t \rightarrow 0$ limit corresponds to open sector UV, closed sector IR.

At this point, a brief discussion of some recent technical results of open string field theory is appropriate since they appear to resolve a potential conflict with this simple qualitative picture of the UV to IR correspondence. In open string field theory the pole of the closed sector actually arises in a different way. It still occurs at the $t \rightarrow 0$ limit, but with the closed tubes pinching off at a point and effectively both t and the string length L going to zero at the pole. [15] However, this type of pinching off actually seems to be an inconsistent description of the closed sector pole and is actually signaling an anomaly and loss of conformal invariance. [5] Proper incorporation of the closed sector appears to be able to cancel the anomaly, at least at one loop. [5] In that sense the closed sector is like a Wess-Zumino term; certainly a different way of looking at the composite graviton. On the other hand if this anomaly cancellation program can be successfully completed, with conformal invariance intact the world sheet view should again have validity, at least in a qualitative sense. That is, the spacetime string field theory view with an anomaly and a compensating closed sector, and the world sheet view of the

closed sector as a well behaved conformal limit of the modular parameter t , may be equally valid ways of looking at the same composite closed sector. Certainly, with all the insights that have come from the world sheet view it does not seem unreasonable to retain the general world sheet view and retain the qualitative features of the UV to IR correspondence discussed above.

Now we turn to our second input which is the observed standard model particles and energies which we want to impose while retaining our stringy view of the open and closed sectors with a composite closed sector. Of course there is no reason to assume our simple open-closed correspondence at a highly symmetrical string scale starting point should survive the “field theory limit” (as well as a complicated combination of compactification and symmetry breaking effects). However, the goal here is to simply assume some of this stringy open- closed amplitude correspondence does survive at low energy and see if the open sector can provide some clues to the closed sector.

As a first guess, it could be reasonably expected that the edges of moduli space dominate the low energy limit for both the planar (annulus) and nonplanar (cylinder) amplitudes. Therefore, we should look there for signals that stringy effects can survive at low energies in the closed sector, using the open sector as a guide. Therefore, let us initially ignore the interior of moduli space and just consider the edges.

First of all, the correspondence at the $t \rightarrow 0$ part of moduli space appears qualitatively unchanged at low energies in the open and closed sectors. The UV sector of the standard model still blows up which we may still equate to the pole in the closed sector as before. Therefore, a massless composite graviton correlating to the open sector loops could still be a consistent part of the theory we see at low energy. The other edge of moduli space is defined by the $t \rightarrow \infty$ limit. This limit of the annulus is defined by the largest color/charge singlet loops; the IR edge of the standard model (open string) sector. This edge clearly has changed. This edge is defined by the mass of the lightest standard model particle with a color/charge singlet vacuum loop diagram, namely the neutrino. We will assume the amplitude structure correspondence has remained the same at this edge. A corresponding change in the closed sector at this edge thus requires a cut off of the cylinder at a finite value. In the closed sector this does not affect the massless pole structure, which comes from the other edge of moduli space, but it does impose a UV cut off. Therefore, since our cylinder diagram is the graviton propagator we get a UV graviton energy cutoff which corresponds to the neutrino mass edge

of moduli space. Therefore, even if we assume that only the correspondence of the open and closed amplitudes at the edges of moduli space survives at low energy we get a departure from a conventional low energy effective field theory of gravity and get a UV gravity cutoff. This is potentially the low energy stringy effect we were looking for.

However, at this point a potential problem presents itself. Why should the neutrino, or any standard model fermion, have anything to do with gravity or the cosmological constant problem? The graviton is a spin two mode of the superstring and the fermion vacuum loops are spin zero. Why should the latter have anything to do with the former? Actually this is not an inconsistency. First of all, the cosmological constant problem in a Feynman diagram sense is related to the graviton tadpole. To avoid violation of Lorentz invariance this tadpole must be the scalar mode of the graviton. Viewed from a classical field theory sense (i.e., linearized general relativity), while the scalar mode of the graviton can be globally gauged away in the absence of matter, it can only be gauged away locally in the presence of matter. Since the vacuum energy/cosmological constant is effectively the same as a matter term, the scalar mode cannot be gauged away globally, only locally, if a cosmological term is present. Therefore, the cosmological constant problem inherently is rooted in the scalar component of the graviton.⁷ Also, the scalar component of the graviton includes the dilaton which is also present in the closed sector. As in conventional string theory approaches the dilaton couples to the effective gravitational constant (G). Therefore, the neutrino edge of moduli space can indeed be relevant to both the cosmological constant and the full effects of gravity.

This leads to another issue which is whether we can find a possible open sector equivalent of the spin two component of the graviton. This spin two mode presumably could only correlate to the nonAbelian gauge bosons of the open sector since fermion vacuum loops cannot create a spin two mode.⁸ Actually such a nonAbelian gauge boson \leftrightarrow gravity correspondence has been identified and extensively studied (in a different context) and indeed graviton vertices can be consistently mapped to direct products of nonAbelian gauge amplitudes. [11]

Therefore, in principle both the scalar/dilaton and spin two modes of the

⁷For a brief early discussion of the graviton tadpole and cosmological constant see [9] and more recently [10].

⁸The apparently contrary claims of [12] have not been carefully examined, however.

closed string sector can be accommodated in the open string sector. One way to look at the resulting graviton structure is that the compositeness we have added in, along with the stringy UV cutoff, is effectively encoded in the dilaton, while the spin two mode incorporates the standard massless pole structure. This seems reasonable since the dilaton reflects the freedom to rescale the closed loop size and it could logically encode all the effective graviton size of the composite graviton.

Another way of looking at the reason a stringy effect remains at low energies is the different nature of the field theory limit in a composite model. In the field theory limit the string length goes to zero. In a conventional closed string model the closed string loop circumference goes to zero and the closed string shrinks to a point. In the composite model the length of the open string still goes to zero but the closed loop remains finite. Only by turning off quantum effects could the loop size be affected, but then it disappears rather than shrink to a point. This highlights the quantum origins of the closed sector in such a composite model. This has already been evident for some time from the appearance of \hbar in the closed sector coupling constant in the open-closed string field theory of [8] and the composite string field theory model of [4].

The application of our stringy UV gravity cutoff to the cosmological constant problem is straightforward. To make a naïve estimate of the value of the cosmological constant we can simply look at the highest energy gravitons as these will give the biggest contribution. As discussed above this correspond to the UV cutoff or the largest loops of the open sector, which corresponds to the neutrino mass edge of moduli space. The neutrino mass has been estimated to be on the order of 10^{-3} eV. This is of the same order of magnitude as the current estimates of the dark energy or effective cosmological constant. Although this could be a coincidence it is at a minimum very suggestive.

Assuming from the above that there are stringy effects missing from the classical gravity sector, and in particular in the gravity UV region, we can try to make a phenomenological adjustment to the graviton propagator. We can simply modify the form of the propagator to include the UV edge of moduli space as follows:

$$D(k) \sim F(k)_{UV}(1/k^2)$$

where the graviton tensor indices are suppressed and $F(k)_{UV}$ has a momentum dependence with a cutoff at the UV energy edge of the moduli space

as signaled by the neutrino. $F(k)$ cannot, however, affect the simple pole structure of the propagator to avoid violating unitarity. For example, the following $F(k)$ may provide the desired cutoff without affecting the basic long range graviton pole:

$$F(k)_{UV} = 1/(A + Be^{k/C-1})$$

where $C \sim 10^{-3}$ eV and A and B normalize $F(k)$ to 1 outside of our cutoff regime (the possibility that B could include a very slow k dependence is discussed in the next section). More complicated forms of $F(k)$ are of course possible and cannot be ruled out other than by experiment or a detailed model.

At a Lagrangian level the modifications due to the composite graviton are straightforward in principle. The conventional string theory derived effective Lagrangian density for gravity is of the following form:

$$L = \frac{1}{2k^2} \sqrt{|g|} e^{-2\phi} (R + 4\partial_\mu \phi \partial^\mu \phi + \dots)$$

where ϕ is the dilaton, R is the Ricci scalar and \dots indicates higher order terms. The gravitational constant G is determined via $e^{-2\phi}/k^2 \sim G$. As discussed above, the light fermion/UV gravity cutoff corresponds to the scalar sector of the graviton which mixes with the dilaton. Therefore, this cutoff can be simply incorporated into the standard Lagrangian by incorporating this into the dilaton potential. One difference, however, is the relation between the dilaton in the open and closed sectors. In the present model the dilaton is a composite so the manner in which the dilaton mixes with the open sector should in general differ from conventional derivations of the dilaton-matter coupling. This composite dilaton could potentially lead to a dilaton which decouples from matter or more generally a dilaton potential similar to that proposed in the decoupling mechanism of [14] which has a number of desirable features. This could also remove the direct link between time variation of standard model coupling constants and the dilaton potential relevant to the gravitational sector which could actually lessen some experimental constraints within the present model.

3. FURTHER POSSIBLE STRINGY CORRECTIONS

The above modification of the closed string/gravity sector only incorporates the modified neutrino defined UV edge of the moduli space. A question obviously arises whether or not the rest of the moduli space other than the

neutrino edge further modifies the graviton propagator. The open string sector/standard model has a complicated mass structure for particles that have singlet loop graphs which could potentially be parts of the same “edge” of moduli space and signal effects in the closed sector. It is at least conceivable that this additional structure of the standard model could be encoded in the graviton/dilaton without violating observational tests of GR. For example, the details of the UV to IR correspondence of this “edge” of moduli space (which will also be affected by compactification) could put these other variations in gravity so far in the IR long distance regime that they are not in conflict with experimental tests of GR; possibly even outside the observable cosmological horizon.

Therefore, whether or not observable, a modification to the graviton propagator of the following generic form is possible:

$$D(k) \sim \sum_i F(k)_i (1/k^2)$$

where the sum is over the mass sectors of the standard model. As one example, we could have:

$$F(k)_i = 1/(A_i + B_i e^{k_i/C_i - 1})$$

where the C_i are the respective mass cutoffs and A_i and B_i are respective normalizations to adjust the relative contribution of the different standard model mass sectors. In terms of the gravitational coupling this would translate via the dilaton to an unusual step type variation in G . Since the details of the open-closed correspondence are unknown a more generic form of $F(k)$ could also include a slow “conformal mapping factor” by giving B a slow dependence on k , but which cannot introduce any cuts into the propagator.

If these modifications are within observable distance these contributions to the graviton propagator and G must be small relative to the neutrino scale UV cutoff effect to not conflict with experiment. However, this is not unreasonable to expect from the results of compactification, the relative effect of the interior of the moduli space to the moduli edge contributions, and the details of the UV to IR map. It is therefore interesting to consider such small but nonzero long distance modifications for galactic or cosmological constraints. In this regard, the data supporting MOND as an alternative to dark matter suggest that some long range modifications of this type are not ruled out experimentally. The k dependence of the graviton propagator

could naturally tie in to an acceleration threshold dependence as required by MOND. The unusual step type dependence could be an advantage in this setting. In any event if some component of this part of the moduli space is nonzero in the long range graviton propagator, no matter how small, it would provide an interesting new way to look for clues to this open-closed correspondence in the large scale gravitational dynamics of the universe.

4. THE STRINGY GRAVITON AND INFLATION

One generic problem with any composite graviton as a solution to the cosmological constant problem is that the effective cosmological constant not only needs to be small but nonzero now but must also have been large during the early universe. If the graviton has a high energy cut off due to a composite structure it should be irrelevant in the early universe but inflation requires a large gravitational negative energy density. Nonetheless, the present model is not incompatible with strong gravitational effects at early times. This follows because the graviton UV cutoff is tied to the light but nonzero lightest fermion mass scale. This fermion mass scale doesn't emerge until after a phase transition well along in the evolution of the universe (relatively speaking). No limitation on the $t \rightarrow \infty$ edge of the modular integration is present before then. Therefore, during the early inflation era the above discussed UV cutoff is not present and Λ is not limited by this cutoff.

Indeed the early universe Λ could have its normally predicted high value expected from vacuum quantum effects which alone could potentially drive inflation and potentially replace the inflaton. A mass generating phase transition could trigger the end of inflation. It would certainly be desirable to avoid the at present essentially ad hoc inflaton field. On the other hand such a model has a number of potential hurdles. The viability of this type of scenario would depend on the details of the initial string theory vacuum state and how supersymmetry could be incorporated into such a model while allowing a large Λ at early times. This would presumably require either a natural string theory ground state with unbroken supersymmetry and large Λ or a mechanism to break supersymmetry in the early universe and start inflation. Also, how this approach could give all the necessary features of inflation without an inflaton potential is not clear. Nonetheless, there conceivably is room for an inflation scenario with a composite graviton and without an inflaton. At a minimum the ability to accommodate both a large early effective Λ and a small nonzero Λ now is an important feature for compatibility with inflation. It seems likely, however, that the correct description

of the composite graviton's role in the early universe will require a completed open string field theory or other nonperturbative formulation and our simple world sheet view will be inadequate to answer these questions.

5. OTHER POSSIBLE FEATURES

At the simplest level the composite graviton model discussed above simply imposes a UV cutoff to gravity. Even limited to this apparently simple phenomenological modification, however, the model potentially has desirable features other than shedding light on the cosmological constant problem. A UV cutoff could remove the singularity problems which plague classical general relativity. Since the composite graviton is inherently stringy in nature it preserves the string theory insights into black hole entropy and could provide further insights in this direction. Also, the UV to IR map is suggestive of AdS/CFT and this in turn suggests that a holographic interpretation could be found. Also, the connection between the hierarchy problem and the cosmological constant problem which emerges naturally is quite appealing. Therefore, even at the simplest level, a stringy composite graviton has far reaching implications.

Also, the model has testable features. Although the UV cutoff is consistent with present experimental limits, variations in G below the neutrino mass scale should be detectable in the not too distant future. This basic signature is shared with the “fat graviton” model of R. Sundrum [3]. In addition, due to the relation of the effective Λ to mass generation of the lightest fermion (neutrino) other even more unique signatures are possible.⁹

6. DISCUSSION

The foregoing is a highly qualitative argument for a possible way out of the cosmological constant problem in the context of the closed string sector emerging out of a purely open string theory. At its most basic the argument is that we should not simply collapse the graviton to a simple field theory pole in an effective field theory approach to gravity as this ignores stringy aspects of the graviton. Also, the appearance of the lightest fermion (neutrino) mass apparently at the same order of magnitude as the observed dark energy is certainly at least suggestive that the observed standard model can give insight to this missing stringy structure of the graviton. Therefore, it seems a reasonable argument can be made for a graviton with a stringy composite structure.

⁹The specifics of such potentially testable signatures are currently being explored further.

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